JEDEC
STANDARD

Implementation of the Electrical Test Method for the Measurement of Real Thermal Resistance and Impedance of Light-Emitting Diodes with Exposed Cooling

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JESD51-51

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JEDEC SOLID STATE TECHNOLOGY ASSOCIATION

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IMPLEMENTATION OF THE ELECTRICAL TEST METHOD FOR THE MEASUREMENT OF REAL THERMAL RESISTANCE AND IMPEDANCE OF LIGHT-EMITTING DIODES WITH EXPOSED COOLING SURFACE

CONTENTS

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Foreword

This document has been prepared by the JEDEC JC-15 Committee on Thermal Characterization. It specifies the details and provisions of physically meaningful thermal characterization of power LEDs.

Introduction

The purpose of this document is to specify, how LEDs's thermal metrics and other thermally-related data are best identified by physical measurements using well established testing procedures defined for thermal testing of packaged semiconductor devices (published and maintained by JEDEC) and defined for characterization of light sources (published and maintained by CIE – the International Commission on Illumination).

This document focuses on **thermal** characterization of LEDs – as special, packaged discrete semiconductor devices. However, whenever needed, reference to light measurement is also made where terms, definitions and symbols specified and used in the relevant document of the *International Commission on Illumination* (CIE), (CIE 127:2007) will be used or referred to.

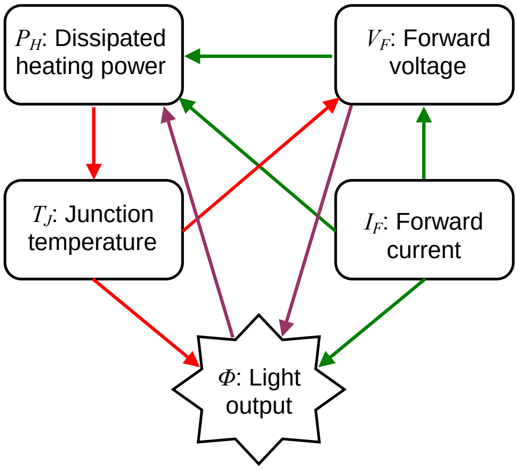
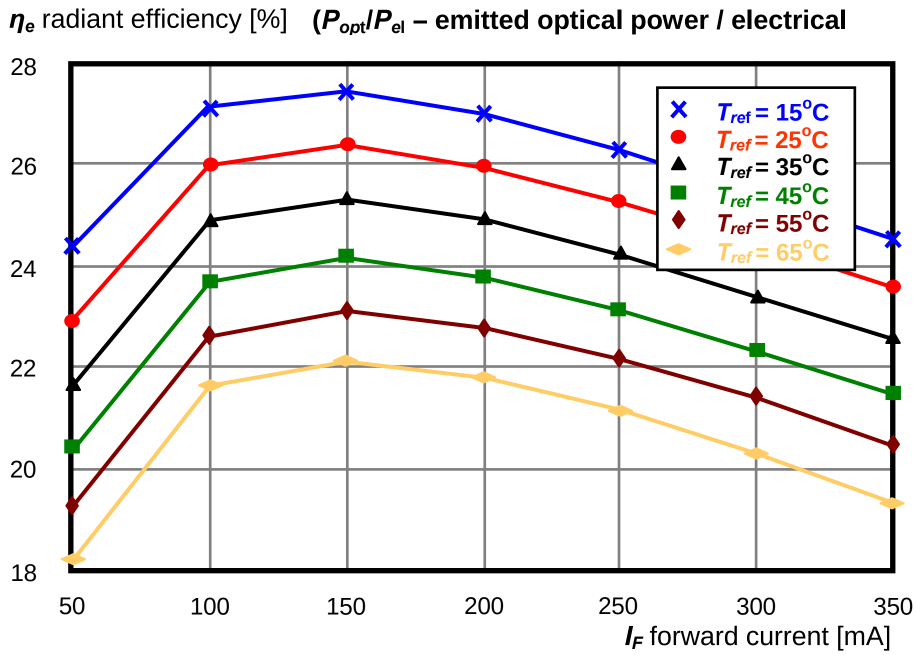


Figure 1 — The mutual dependence of LEDs's light output and different (macroscopic) quantities characteristic to the LEDs' operating conditions

LED specific aspects of thermal testing procedures are defined in a generic way which means, that whenever possible, no distinction is made between steady-state and dynamic (transient) thermal measurements. Thus, this document belongs to the JESD51-50 through JESD51-53 series of standards. The overview of these standards is provided in the JESD51-50 document, (*Overview of Methodologies for the Thermal Measurement of Single- and Multi-Chip, Single- and Multi-PN-Junction Light-Emitting Diodes (LEDs)*). This document should also be used in conjunction with the JESD51 series of standards, especially with JESD51-1 (*Integrated Circuit Thermal Measurement Method - Electrical Test Method*) and JESD51-14 standard about junction-to-case thermal resistance measurement (*Transient Dual Interface Test Method for the Measurement of Thermal Resistance Junction-to-Case of Semiconductor Devices with Heat Flow through a Single Path*).

Introduction (cont'd)



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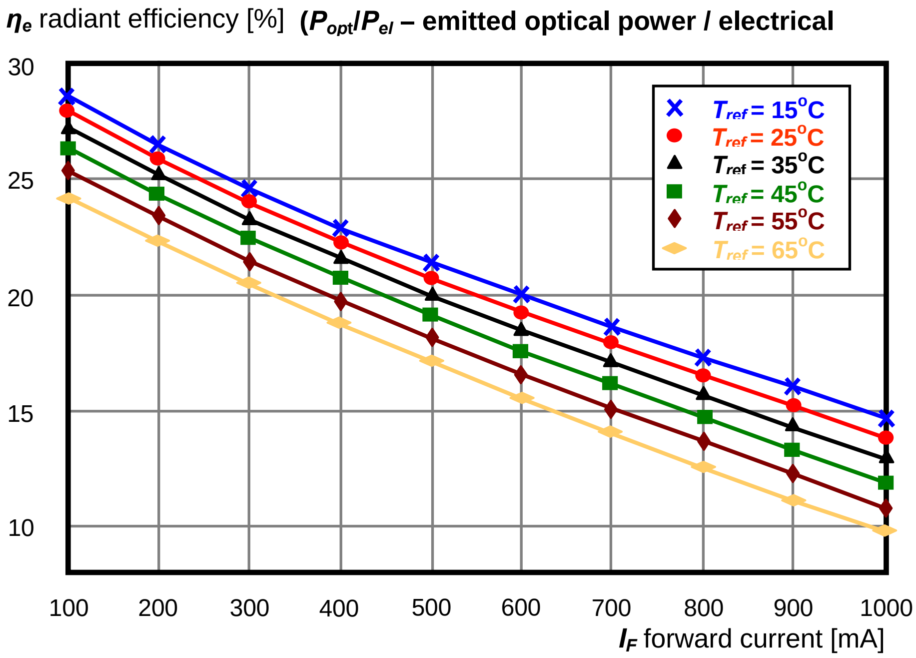

2b)

Figure 2 — Temperature and forward current dependence of the energy conversion efficiency (also known as radiant efficiency) of two different power LEDs

The reason why these guidelines are provided specifically for LEDs is that the physics determining their thermal behavior is more complex than in case of conventional semiconductor devices which are not aimed at emitting any kind of electro-magnetic radiation like visible light.

Introduction (cont'd)

Thermal characterization of LEDs is a special case of thermal characterization of semiconductor diodes. The need for measurement guidelines for LEDs has arisen when light-emitting diodes with high power and high energy conversion efficiency emerged.

This complexity in the physics – as illustrated by Figure 1– becomes manifest in the following:

- The electric to light energy conversion efficiency is determined by the operating conditions of the LED: the junction temperature and the applied forward current. This efficiency is not a single number since it depends both on the LED's junction temperature and forward current as shown in Figure 2a and 2b.

- The power dissipated at the active region of a LED is thus determined by the difference of the supplied total electrical energy ($V_F \cdot I_F$) and the total energy emitted as optical radiation (Φ_e – emitted total radiant flux, also denoted as P_{opt}):

  $$P_H = V_F \cdot I_F - \Phi_e \qquad (1)$$

  This power together with the thermal resistance of the LED determines the junction temperature. In some cases it is recommended to add another loss term, P_{loss}, that describes extra losses such as light absorption in the lens (ideally it is negligible) and energy loss in the phosphor (in case of white LEDs). In practical cases these hardly can be measured separately, therefore are not accounted for.

IMPLEMENTATION OF THE ELECTRICAL TEST METHOD FOR THE MEASUREMENT OF REAL THERMAL RESISTANCE AND IMPEDANCE OF LIGHT-EMITTING DIODES WITH EXPOSED COOLING SURFACE

(From JEDEC Board Ballot JCB-12-08, formulated under the cognizance of the JC-15 Committee on Thermal Characterization.)

1 Scope

This document specifies thermal testing procedures for power light-emitting diodes (power LEDs) and/or high brightness light-emitting diodes (HB LEDs) – in the following referred to as LEDs – which are typically used in the operating regime of the forward current of 100mA and above, and emit visible light^1)^.

The application of these measurement guidelines is recommended for packaged LEDs, 1) with a total electrical power consumption above 0.5 W, 2) which have energy conversion efficiency above 5%, and 3) that are powered by steady DC power (typically with forced constant forward current), regardless whether the LED device inside the package is realized as single chip or multi chip device. Further details of the definition of term *LED* or *LED device* used in this document are given in section 0. This document does not deal with laser diodes.

When speaking about thermal testing, one can distinguish between laboratory testing and bulk testing. The scope of this document is laboratory testing of power LEDs.

Recommendations given in this document are valid for both steady-state and dynamic (transient) thermal measurements of LEDs, both relying on *JEDEC JESD51-1 electrical test method*. For steady-state thermal metrics both the *static* and *dynamic* test methods defined in JESD51-1 can be used.

Regarding the *heating power*, this document is aimed as an LED specific extension of the JEDEC JESD51-14, *Transient Dual Interface Test Method for the Measurement of Thermal Resistance Junction-to-Case of Semiconductor Devices with Heat Flow through a Single Path* document, applicable for DC driven LEDs only. Further LED specific additions to JESD51-14 may also be published in the future which would deal with practical aspects of the differences between power LED packages and other power semiconductor device packages.

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(1) Strictly speaking, the term LED should only be applied to those diodes which emit visible light. Those, which emit infra-red or UV radiation, should be referred to as IR LEDs or UV LEDs.

2 Normative references

The following normative documents contain provisions that, through reference in this text, constitute provisions of this guideline. For dated references, subsequent amendments to, or revisions of, any of these publications do not apply. However, parties to agreements based on this standard are encouraged to investigate the possibility of applying the most recent editions of the normative documents indicated below. For undated references, the latest edition of the normative document referred to applies.

JESD51, *Methodology for the Thermal Measurement of Component Packages (Single Semiconductor Devices).*

JESD51-1, *Integrated Circuit Thermal Measurement Method - Electrical Test Method.*

JESD51-12, *Guidelines for Reporting and Using Electronic Package Thermal Information.*

JESD51-13, *Glossary of Thermal Measurement Terms and Definitions.*

JESD51-14, *Transient Dual Interface Test Method for the Measurement of Thermal Resistance Junction-to-Case of Semiconductor Devices with Heat Flow through a Single Path.*

JESD51-50, *Overview of Methodologies for the Thermal Measurement of Single- and Multi-Chip, Single- and Multi-PN-Junction Light-Emitting Diodes (LEDs).*

JESD51-52, *Guidelines for Combining CIE 127-2007 Total Flux Measurements with Thermal Measurements of LEDs with Exposed Cooling Surface.*

JESD51-53, *Terms, Definitions and Units Glossary for LED Thermal Testing.*

CIE S 017/E:2011 ILV, *International Lighting Vocabulary.*

CIE 127:2007 Technical Report, *Measurement of LEDs*, ISBN 978 3 901 906 58 9.

MIL-STD-750D METHOD 3101.3, *Thermal Impedance (Response) Testing of Diodes*.

ANSI/IESNA IES Nomenclature Committee, IES RP-16-10, *Nomenclature and Definitions of for Illuminating Engineering*, ISBN 978-0-87995-208-2

ANSI/IESNA IES-LM-80, *Approved Method for Measuring Lumen Maintenance of LED Light Source*s, ISBN 978-0-87995-227-3.

3 Terms and definitions, notations

3.1 Symbols and terms

In this document the notations employed in the JESD51, JESD51-1, JESD51-12, JESD51-13 and JESD51-14 are used. Generic terms and quantities related to light output measurement are used as defined in the *International Lighting Vocabulary*, CIE S 017/E:2011 ILV; LED specific terms of photometry and radiometry given in CIE 127:2007 are used. The most important terms and notations referred to in this document are listed in Table 1. Comprehensive descriptions of terms, definitions and units used in conjunction with LEDs are provided in JESD51-53. For terms and definitions not listed there refer to JESD51-13, CIE S 017/E:2011 ILV and ANSI/IESNA RP-16-10.

Table 1 — Symbols used in this document

Symbol	Unit of measure	Name, description
T_J	[^{o}C]	**junction temperature** (see JESD51-1) of the LED, denoted and referred to as T_C , the *chip temperature*, in CIE 127:2007. (In the temperature range of interest, the usage of [^{o}C] is more common.)
ΔT_J	[^{o}C] or [K]	**change of junction temperature** (see JESD51-1, JESD51-50). For temperature differences [^{o}C] is commonly used.
$R_{\theta JX}$, R_{thJX}	[K/W]	**junction-to-specific environment thermal resistance** (see JESD51-1, JESD51-50) where x refers to the environment in question.
θ_{JX}	[K/W]	**alternate symbol to $R_{\theta JX}$** (see JESD51-1, JESD51-50).
Ψ_{JX}	[K/W]	**junction-to-X thermal characterization parameter**, (see JESD51-13).
V_F	[V]	**junction forward voltage**
I_F	[A]	**junction forward current**
P_H	[W]	**heat dissipated at the junction of the LED** (see JESD51-50), also denoted as P_H and referred to as heating power in (see JESD51-1, JESD51-14 and MIL-STD-750D METHOD 3101.3) .
P_{opt}	[W]	**emitted optical power of the LED** referred to as *total radiant flux* and denoted as Φ_e in CIE S 017/E:2011 ILV. It is also called *radiant power*.
P_{el}	[W]	**electrical power supplied to the LED** which is equal to the product of the forward voltage and the forward current: $P_{el} = V_F \cdot I_F$. This quantity is denoted as P in CIE 127:2007.
Φ_e	[W]	**emitted optical power of the LED**, alternate notation to P_{opt} as defined and referred to as *total radiant flux or radiant power* (see CIE S 017/E:2011 ILV).
η_e, WPE	[%]	**radiant efficiency** or *energy conversion efficiency* or *wall plug efficiency* of the LED: 100 × value of the P_{opt} emitted optical power divided by the P_{el} supplied electrical power. Throughout this document WPE is defined for a single LED device.
η_V	[lm/W]	**efficacy** (short hand for *luminous efficacy* of a source as per CIE S 017/E:2011 ILV) the value of the LED's emitted total luminous flux Φ_V divided by the P_{el} supplied electrical power.
z	s	**logarithmic time**, the absolute value of this quantity is defined as $z = \log(t)$.
$Z_{\theta JX}$, Z_{thJX}	[K/W]	**junction-to-specific environment thermal impedance**, the temporal change of junction temperature with respect to temperature of environment X, normalized to 1W heating power and scaled in z logarithmic time.
TSP	n.a.	**temperature sensitive parameter,** in case of semiconductor diodes it is the V_F forward voltage.
S_{VF}	[mV/K]	**temperature sensitivity of the forward voltage**, measured at I_M measuring current (also called as sensor current).
K	[K/mV]	**K-factor**, reciprocal of the S_{VF} temperature sensitivity of the forward voltage, identified at I_M measuring current (also called as sensor current).
I_H	[A]	value of the forward current of the LED applied as *heating current.*
V_H	[V]	value of the forward voltage of the LED when biased by the heating current.
I_M	[mA]	value of the forward current of the LED applied as *measuring current.*
t_{MD}	[s]	**measurement delay time**, time elapsed between the instance of switching the power applied to the LED under test and the instance of the first reading of the TSP not disturbed by electrical transients.
V_{Fi}	[V]	initial value of the forward voltage of the LED immediately after switching the power across the diode.
V_{Ff}	[V]	final value of the forward voltage of the LED when diode reached its final thermal steady-state after switching the power.

3 Terms and definitions, notations (cont'd)

3.2 Definition of LEDs

The everyday term (high) *power LED* is somewhat ambiguous, since there is a tendency that multiple single pn-junction LED chips are packaged into a single package (sharing the same cooling assembly and optics) or multiple elementary pn-junctions on a single chip form an LED device. Also, in many cases multiple packaged LEDs are assembled to a substrate (usually a high thermal conductivity board such as a metal core PCB or MCPCB in short) to form one single device. In many cases these devices – internally formed as arrays of elementary light-emitting diodes – have only limited number of electrical connections to the outside world: this way the electrical circuitry for most high power LED arrays does not allow for connection to an individual diode. With only two electrical contacts, the thermal measurement must treat the entire array as a single diode. The implication of this reality is that the junction temperature measurement results actually in a weighted average of multiple junction temperatures and there is also limited ability to relate the measured temperature to a spatial location within the array. Figure 3 illustrates the different possible electrical configurations – as an example – for a 3×3 physical arrangement of single light-emitting diodes.

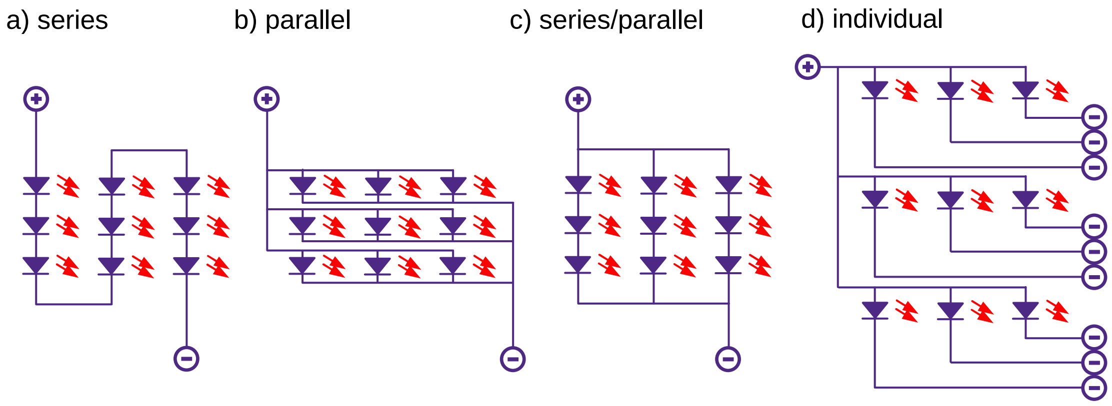

Figure 3 — Different LED array configurations

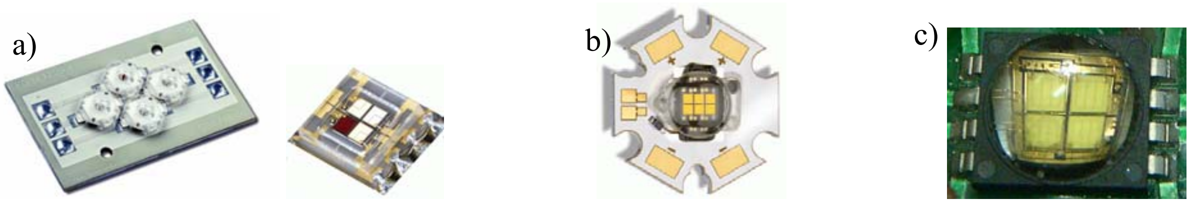

Figure 4 — Examples of LED array devices: a) RGB modules with individually accessible LEDs (single MCPCB with multiple packages, single package with multiple chips), b) multi-chip single package LED light source on an MCPCB substrate, c) single package multi chip LED device with individual access to each chip inside the package

An LED array is defined as two or more individual LED chips mounted in a package or on a substrate in a manner such that any device in array can be powered through either series, parallel or individual connections while the other devices in the array may or may not be operating. The individual LED chips may also consist of an array of LED junctions on the chip as well.

3 Terms and definitions, notations (cont'd)

3.2 Definition of LEDs (cont'd)

Thermal measurements on an LED chip array can either be done on the array as a whole or on individual chips within the array, depending on the electrical connections available. Figure 3 presents schematics for different electrical connection alternatives. The *Series configuration* requires the highest power supply voltage but also requires the lowest current. Conversely, the *Parallel configuration* requires the highest current but the lowest voltage$^{2)}$. The Series/Parallel configuration requires moderate current and voltage and, by modifying the series and parallel arrangement, can be more easily tailored to meet specific application requirements. The Individual configuration, shown in Figure 3 with a *common anode* connection, is most often used when the LEDs are dissimilar, i.e., different color, etc. Other Individual configurations include separate contacts for each device, X-Y addressing and *common cathode*. Practical (product) examples of LED array devices are shown in Figure 4. Thermal measurements of any of these array configurations are necessary to ensure that each array element is operating in an acceptable junction temperature (T_J) range for that specific element.

When the array product is available only in packaged form with only the + and – leads/contacts available (Figure 3b), the array can only be measured as a composite LED. All measured characteristics (thermal resistance, temperature sensitivity of the overall forward voltage, radiant flux, luminous flux, color, etc.) of such an array are *ensemble characteristics* of the array. In such cases the array is considered as a single chip equivalent device which possesses the measured ensemble characteristics of the array device, i.e., the data results will assume equal power distribution and the same value of temperature-sensitive parameter (TSP) variation and the same junction temperature change (ΔT_J) for each LED in the array.

In the subsequent sections under term LED (or power LED) or LED device we mean either an individually available single LED of any LED array arrangement or an equivalent LED of an LED array where elements of the array are not accessible individually (this equivalent LED being characterized by its ensemble characteristics) with an exposed cooling surface that will be heat sunk during normal operation. This cooling surface could be the cooling tab (heat-slug) of a single packaged LED device (usually referred to in the solid-state lighting industry as *level0* device) or a packaged LED device attached to a substrate (such as an MCPCB as shown in Figure 4b – these are usually referred to in the solid-state lighting industry as *level1* device), see also definition 6.8.5.1 of LED packages and definition 6.8.5.2 of the LED arrays or modules in *ANSI/IESNA RP-16-10 Nomenclature and Definitions for Illuminating Engineering*. The scope of this document does not include any other solid-state lighting device defined in ANSI/IESNA RP-16-10.

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2) Because of possible high voltage or high current, the requirements of the device under test may exceed limits of certain commercially available thermal test equipment. Therefore vendors of test equipment may provide so called power boosters which meet voltage/current specifications of LED arrays – these may be commercially referred to as *LED boosters*.

4 Junction temperature, thermal resistance/impedance

The key thermal parameters of semiconductor devices are junction temperature, T_J, and thermal resistance, $R_{\theta JX}$ or θ_{JX} (see JESD51-50, JESD51-1 and MIL-STD-750D Method 3101.3):

$$T_J = T_{J0} + \Delta T_J \tag{2}$$

where

T_{J0} is the junction temperature before application of dissipation (heating power), also known as the adiabatic temperature;
ΔT_J is the change of junction temperature as a response to the change in the dissipated power.

Under carefully defined conditions for a specific environment *X*, the change in junction temperature – with respect to the T_X, reference temperature of environment X, can be determined as follows (see JESD51-50):

$$T_J = P_H \cdot R_{\theta JX} + T_X \tag{3}$$

or

$$[\Delta T_J]_X = T_J - T_X = P_H \cdot R_{\theta JX} \tag{4}$$

where

P_H is the dissipated power in the device;
$R_{\theta JX}$ is the thermal resistance from the device junction to the specific environment *X*.

By rearranging the equation (3), the thermal resistance of the device is commonly expressed as follows (see JESD51-1, page 3 and MIL-STD-750D Method 3101.3, page 6):

$$R_{\Theta JX} = \frac{T_J - T_X}{P_H} = \frac{[\Delta T_J]_X}{P_H} \tag{5}$$

The condition for being able to calculate the junction-to-X thermal resistance as $[\Delta T_J]_X$ / P_H (see JESD51-1, page 3, paragraph 4) is that initially when $P_H = 0$, $T_J = T_X$ and during the test T_X is kept constant[3)].

Regarding LEDs within the scope of this document, the junction-to-case thermal resistance and/or the junction-to-case thermal impedance is the most relevant thermal metric. In this document discussion is restricted to the measurement of these properties by using the JESD51-1 static test method.

To allow measurement of the emitted *optical power* of LEDs (also known as *radiant power*) with a procedure compatible with the recommendations of CIE for the measurement of LEDs's light output, thermal steady state of the LED under test must be provided when its emitted optical power is measured. Therefore measuring of LEDs's thermal characteristics is recommended in cooling mode (as illustrated in Figure 5), and this method is also in compliance with JESD51-14.

[3)] This requirement can be kept for the two extreme cases of test environments: heat-sunk situations (cold-plate environment) and natural convection environments resulting in R_{thJC} junction-to-case and R_{thJA} junction-to-ambient thermal metrics, respectively. For MCPCB assembled LED devices the most relevant metric is R_{thJC}.

4 Junction temperature, thermal resistance/impedance (cont'd)

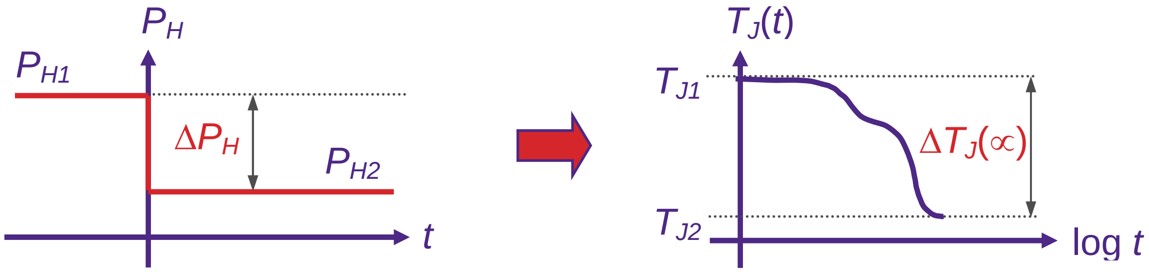

Figure 5 — Junction-to-X thermal resistance calculated from a temporal difference of the junction temperature and the power dissipated in the device

Following the definition given in JESD51-14, the junction-to-X thermal impedance is defined as

$$R_{\Theta JX}(t) = \frac{\Delta T_J(t)}{\Delta P_H} = Z_{\Theta JX} \tag{6}$$

For very long testing times when practically $t=\infty$ (i.e., no considerable change in the junction temperature can be observed), equation (6) defines the steady-state thermal metric $R_{\theta JX}$. When the goal is to measure the steady-state thermal metric $R_{\theta JX}$, the initial and final junction temperatures (denoted by $T_{J1} = T_J(0)$ and $T_{J2} = T_J(\infty)$ in Figure 5) can be measured both by the *static* and *dynamic* test methods defined in JESD51-1. The junction temperature at t=0 must be measured with the possible smallest measurement delay. See further details in section 5.

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5 Measurement procedures recommended for LEDs

5.1 Measurement of LEDs's thermal resistance and junction temperature

5.1.1 The electrical connections and test waveforms

This standard is based on the diode measurement techniques described JESD51-1 and MIL-STD-750 Method 3101.3. As recommended by these standards, junction temperature of LEDs can also be measured with the electrical test method using the four wire test setup (also known as Kelvin-setup) as illustrated by the basic measurement circuit shown in Figure 6. The basic scheme of the test waveform is shown in Figure 7.

5.1 Measurement of LEDs's thermal resistance and junction temperature (cont'd)

5.1.1 The electrical connections and test waveforms (cont'd)

The difference between the V_{Fi}, initial device forward voltage, under low current (I_M) conditions (after switching the device from the I_H heating current to the I_M measurement current) and the V_{Ff}, final voltage, measured at I_M current is directly proportional to the junction temperature change caused by the high current (I_H) heating. This linear dependence of the forward voltage on the junction temperature can be described as follows:

$$V_F(I_M,t) = V_{Fi}(I_M) + S_{VF}\cdot\left[T_J(t) - T_J(0)\right] \tag{7}$$

where $S_{VF} = S_{VF}(I_M)$ is the temperature sensitivity of the forward voltage measured at I_M current, its reciprocal is the K-factor: $K = 1/S_{VF}$. (For further details on K-factor refer to 5.3.)

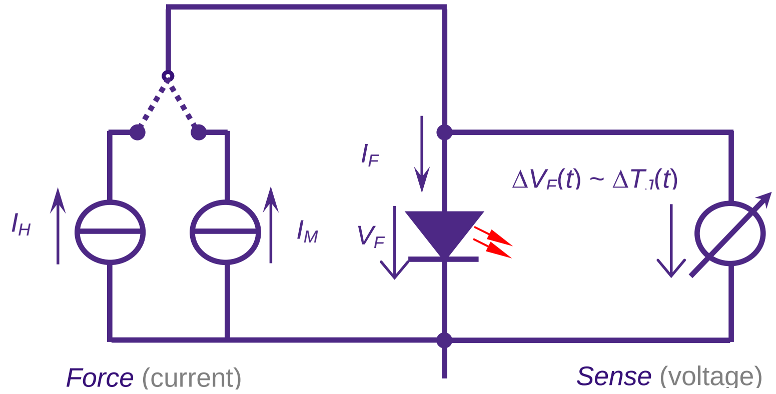

Figure 6 — Diode thermal measurement circuit
(see JESD51, MIL-STD-750D Method 3101.3)

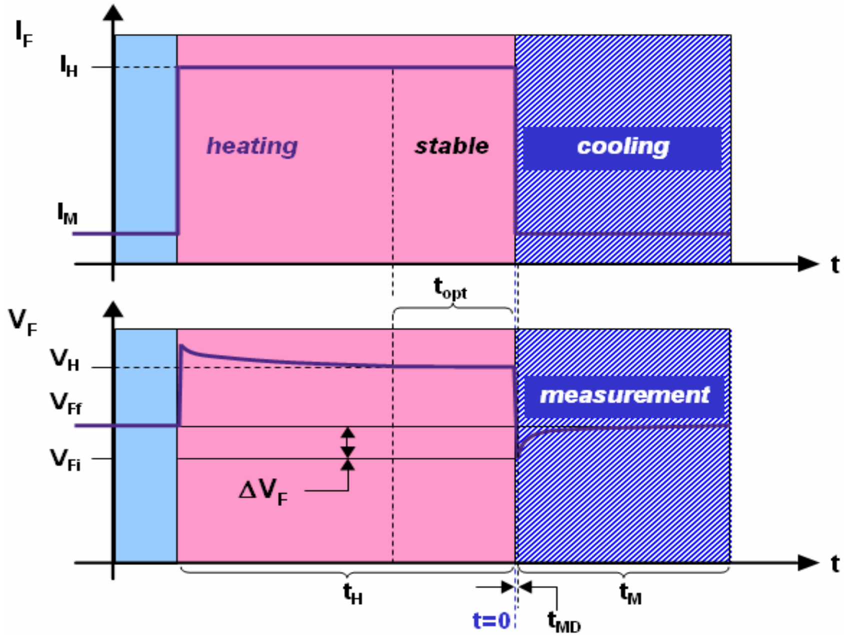

Figure 7 — LED thermal measurement waveform

5.1 Measurement of LEDs's thermal resistance and junction temperature (cont'd)

5.1.1 The electrical connections and test waveforms (cont'd)

Theoretically one has to wait infinite time for the junction temperature – hence the forward voltage – to get stabilized. Therefore, based on equation (7) the V_{Ff}, final value of the forward voltage, after switching the forward current of the LED can be expressed as follows:

$$V_{Ff} = V_F\left(I_M, t=\infty\right) = V_{Fi}\left(I_M\right) + S_{VF}\cdot\left[T_J(\infty) - T_J(0)\right] \tag{8}$$

5.1.2 Measuring LEDs's thermal resistance / impedance using the electrical test method

Based on equation (8), the junction temperature difference in equation (5) is

$$\Delta T_J = \Delta V_F / S_{VF} \tag{9}$$

Using this, the junction-to-reference environment X thermal resistance can be expressed as follows:

$$R_{\Theta JX} = \frac{V_{Fi}(T_{J1}, I_M) - V_{Ff}(T_{J2}, I_M)}{S_{VF}\cdot(P_{H1} - P_{H2})} = K(I_M)\cdot\frac{\Delta V_F}{\Delta P_H} \tag{10}$$

The junction-to-reference environment X thermal impedance introduced by equation (6) can also be expressed by the forward voltage change:

$$Z_{\Theta JX} = K(I_M)\cdot\frac{\Delta V_F(t)}{\Delta P_H} \tag{11}$$

If the emitted optical power in ΔP_H is not considered, thermal resistance and impedance defined by equations (10) and (11) *shall be denoted by* $R_{\Theta JX\text{-}el}$ *and* $Z_{\Theta JX\text{-}el}$, respectively.

Figure 8 presents of the electrical and thermal state transitions of an LED device by means of I-V characteristics after the switching event at t=0 shown in the test waveform of Figure 7.

In order to assure consistency between thermal and light output measurements of LEDs, constant power levels need to be applied. Hereby a test procedure is described which relies on the JESD51-1, *electrical test method*. Using the measurement sequence described in the following constant junction temperature and constant forward current is assured for the duration of the measurement of light output metrics.

Both the original static test method in JESD51-1 – where measuring the junction temperature takes place at the initial thermal steady-state and in the final thermal steady-state of the device under test is performed – resulting in a thermal resistance value as per equation (10) and the real-time transient extension of the static test method – where the junction temperature is continuously measured between the initial and final thermal steady states is realized resulting in time-domain thermal impedances as per equation (11) – can be applied. Test equipment based on the dynamic test method of JESD51-1 can also be used to measure V_{Fi} and V_{Ff} in equation (8).

If the time-domain thermal transient measurement based on the static test method is implemented in an LED testing station, then the transient R_{thJC}, junction-to-case thermal resistance, measurement of LEDs can be performed according to JESD51-14 with some slight modifications regarding the recommendations of the cold-plate and the DUT mounting.

5.1 Measurement of LEDs's thermal resistance and junction temperature (cont'd)

5.1.2 Measuring LEDs's thermal resistance / impedance using the electrical test method (cont'd)

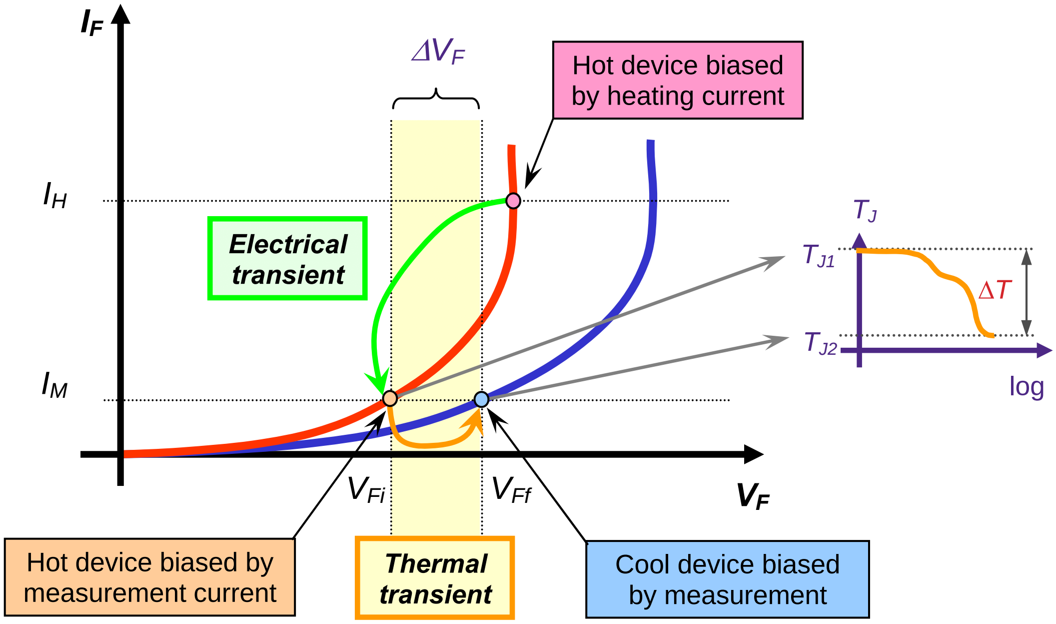

Figure 8 — Electrical and thermal state transitions of an LED shown in the I-V characteristic of the device after time instance t=0, as indicated in the test waveform of Figure 7

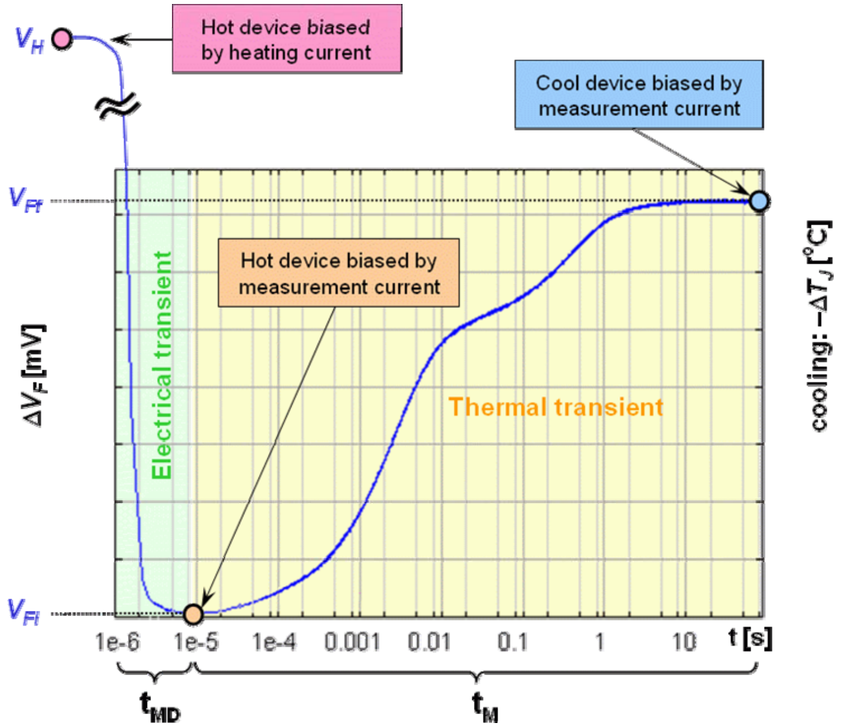

Figure 9 — Electrical and thermal state transitions of an LED shown as a time diagram after time instance t=0 as indicated in the test waveform of Figure 7 – indicating time scales typical for LEDs measured on a cold-plate

5.1 Measurement of LEDs's thermal resistance and junction temperature (cont'd)

5.1.2 Measuring LEDs's thermal resistance / impedance using the electrical test method (cont'd)

In case of thermal resistance characterization of LEDs, measurement of their cooling is recommended for the following reasons:

- This is also the recommendation in JESD51-14. The reason is that the error term in the change of the applied electrical power is negligible in cooling mode (see details in 5.1.5). This assures that the power after the switching remains practically constant which is a theoretical requirement if the measured driving point thermal impedance is to be represented by structure functions. (Find details on structure functions in Annex A of JESD51-14 and further, in the technical literature, Refs. 1 and 2)
- As described in 5.1.6, the preferred testing method for LEDs is to combine thermal and light output measurements in a single test station. The light output measurement procedures of LEDs defined in the CIE 127:2007 standard require the measurements to be carried out in a thermal steady-state when the normal operating current is applied to the LED which means, that cooling of LEDs can be naturally measured after standard light output measurements are completed and the LEDs are switched off. (Recommendations for the implementation of the CIE 127-2007 compliant total flux measurements in combination with thermal measurements of LEDs are provided in JESD51-52.)
- As a consequence of the previous two paragraphs, for the measurement of the $Z_{\Theta JX}(t)$ *thermal impedance* defined by equation (11), the *static test method* of JESD51-1 shall be applied. For the measurement of $R_{\Theta JX}$, thermal resistance, defined by equation (10), both the *static* and *dynamic test methods* defined in JESD51-1 can be used.

5.1.3 Measurement delay and measurement current selection, data correction

Figure 9 shows the time evolution of transients of the forward voltage which were illustrated in Figure 8. These take place when at time instance t=0 the forward current of the LED is switched from the I_H, heating current, to the I_M as shown by the test waveform diagram in Figure 7.

The V_F(t) forward voltage vs. time function starts with a large *parasitic electrical transient* corresponding to the jump from the (V_H, I_H) operating point in the I-V characteristic to the (V_{Fi}, I_M) operating point. This electrical transient is inherently present in the V_F(t) functions of pn-junctions when the forward current of the diode is abruptly switched (in a step-wise manner) between two current levels. The duration of this electrical transient determined by the speed at which the amount of the diffusion charge corresponding to level of the I_H, heating current, can be reduced to the amount of diffusion charge corresponding to the I_M, measurement current. (The speed of the electrical transient is also influenced by the speed of the electronic switch applied to change the forward current from I_H to I_M and by the stray capacitances of the measurement apparatus used.) The smaller the difference between the I_H and I_M currents, the faster the parasitic electrical transient elapses. Applying higher I_M, measurement current, reduces the current difference, thus, reduces the length of the parasitic electrical transient and also allows higher signal-to-noise ratio in the forward voltage measurement. Increasing the value of I_M is limited by the requirement that no significant self-heating of the junction should occur during the K-factor calibration process performed at I_M, measurement current, (see 5.3). In case of typical power LED devices(4) I_M is around 10 mA while typical I_H values are between 350 mA and 1000 mA. In case of blue or white LEDs even 20 mA or higher I_M, measurement current, may be required in order to provide a stable and noise free thermal signal.

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(4) As of early 2010.

5.1 Measurement of LEDs's thermal resistance and junction temperature (cont'd)

5.1.3 Measurement delay and measurement current selection, data correction (cont'd)

The t_{MD} measurement delay time should be chosen such, that the first forward voltage reading corresponding to the junction temperature transient is grabbed. Data sampling may start immediately after switching the forward current from I_H to I_M. Typically there is a minimum point in the V_F(t) forward voltage vs. time function which separates the parasitic electrical transient from the thermal transient (see Figure 9). The duration of the electrical transient is typically between 10 µs and 50 µs. Therefore the t_{MD} measurement delay time should be best chosen to coincide with this minimum point. In case of real-time thermal transient measurements aimed at recording the $Z_{\Theta JX}(t)$, *thermal impedance,* defined by equation (11) the t_{MD} timing parameter is called *cut-off time* and is denoted by t_{cut} in the corresponding standard JESD51-14.

By choosing longer t_{MD} measurement delay, a significant amount of junction temperature change is lost and a large error in the measured ΔT_J value is introduced.

According to equation (9), ΔT_J(t) = $\Delta V_F(t)$ x $K(I_M)$. Data points of the ΔT_J(t) function *corresponding to the parasitic electrical transient of the $V_F(t)$ forward voltage vs. time function must be discarded*. There are LED devices which are thermally much faster than electrically, therefore significant junction temperature change may take place during the t_{MD} measurement delay time even if it is in the order of magnitude of 10 µs. Therefore data correction should not be restricted to discarding the parasitic electrical transient but the *junction temperature transient should be extrapolated back to the time instance of switching.* The extrapolation technique detailed in JESD51-14, 4.1.3 should be applied for this.

5.1.4 Length of the measurement window, heating time

The largest thermal time-constants of power LEDs or power LED assemblies attached onto cold-plates are in the order of magnitude of ~30 s to ~120 s, that is, the cooling transient of the LED's junction temperature spans over this range. Trial measurements should be applied to identify the t_M length of the measurement window (see Figure 7) during which the V_{Ff}, final steady-state value of the forward voltage, is reached. Steady-state is assumed to be reached if the variation of the forward voltage reading shrinks below 0.5% in a time window equal to 1/3 of the length of the already elapsed measurement time.

The t_H heating time must be chosen to be at least 1.5 times the length of the measurement window: $t_H > 1.5 \cdot t_M$ in order to have proper repeatability in measurements following each other. Otherwise a superposition of heating and cooling is seen during the measurement time.

This is required to make sure, that the V_H value of the forward voltage gets stabilized after the I_H heating current is applied to the LED and enough t_{opt} testing time (also shown in Figure 7) is left to perform light output measurements in the stabilized hot operating point of the LED if the thermal testing is combined with light output measurements in an LED testing station. Even if no combined thermal and radiometric measurements of LED are performed, keeping the above requirement is a good a practice. (The lowest theoretical limit of the heating time is the length of the thermal transient of the device therefore the heating time should be at least as long as the length of the measurement window.)

5.1 Measurement of LEDs's thermal resistance and junction temperature (cont'd)

5.1.5 Real heating power of LEDs

The heating power to be considered in case LEDs is the actual power dissipated at the junction which is the difference of the supplied P_{el} electrical power and the emitted P_{opt} optical power. The ΔP_H heating power difference to be considered in equation (10) or equation (11) shall be calculated as follows:

1) The electrical power in the stabilized state when the I_H heating current is applied is the following:

$$P_{elH} = I_H \cdot V_H \tag{12}$$

2) The LED's emitted optical power in the stabilized state when the I_H heating current is applied is equal to the *total radiant flux* of the LED measured at that current and the corresponding T_{J1} junction temperature:

$$P_{optH} = \Phi_e(I_H, \mathrm{T}_{J1}) \tag{13}$$

where

T_{J1} denotes the steady-state junction temperature when the I_H current is applied.

3) The total heating power when the heating current is applied is equal to

$$P_{HH} = P_{elH} - P_{optH} = I_H \cdot V_H - \Phi_e(I_H, \mathrm{T}_{J1}) \tag{14}$$

4) The small heating power caused by the I_M measurement current shall be calculated as

$$P_{elM} = I_M \cdot V_{Fi} + I_M \cdot \Delta V_F(t) \tag{15}$$

5) The LED's emitted optical power when the I_M measurement current is applied is equal to the *total radiant flux* of the LED measured at that current and the corresponding T_{J1} junction temperature:

$$P_{optM} = \Phi_e[I_M, \mathrm{T}_J(t)] \tag{16}$$

6) The total heating power when the measurement current is applied is equal to

$$P_{HM} = P_{elM} - P_{optM} = I_M \cdot V_{Fi} + I_M \cdot \Delta V_F(t) - \Phi_e[I_M, \mathrm{T}_J(t)] \tag{17}$$

7) The ΔP_H corrected with the emitted optical power shall be denoted by $\Delta P_{H\text{-}corr}$ and can be calculated as follows:

$$\begin{aligned}\Delta P_{H\text{-}corr} &= P_{HH} - P_{HM} = I_H \cdot V_H - \Phi_e(I_H, \mathrm{T}_{J1}) - \{I_M \cdot V_{Fi} + I_M \cdot \Delta V_F(t) - \Phi_e[I_M, \mathrm{T}_J(t)]\} = \\ &I_H \cdot V_H - I_M \cdot V_{Fi} - I_M \cdot \Delta V_F(t) - \Phi_e(I_H, \mathrm{T}_{J1}) + \Phi_e[I_M, \mathrm{T}_J(t)]\end{aligned} \tag{18}$$

8) Neglecting terms $I_M \cdot \Delta V_F(t)$ and $\Phi_e[I_M, \mathrm{T}_J(t)]$ cause an error less than 1% in the total power change, therefore the recommended formula for determining the heating power of LEDs is the following:

$$\Delta P_{H\text{-}corr} = I_H \cdot V_H - I_M \cdot V_{Fi} - \Phi_e(I_H, \mathrm{T}_{J1}) \tag{19}$$

5.1 Measurement of LEDs's thermal resistance and junction temperature (cont'd)

5.1.5 Real heating power of LEDs (cont'd)

To estimate the error one makes by neglecting the $I_M \cdot \Delta V_F(t)$ and $\Phi_e[I_M, T_J(t)]$ terms, the measurement example of a 10W white LED (4 chips connected in series) is shown in Figure 10. The total error indicated here is the sum of the neglected terms compared to the total heating power.

V_H	13.240 V
I_H	0.700 A
I_M	0.010 A
V_{Fi}	10.650 V
ΔV_F total	0.300 V
P_{optH}	2.38 W
P_{optM}	0.036 W
$I_H \cdot V_H$	9.268 W
$I_M \cdot V_{Fi}$ (P_S in 0)	0.107 W
$I_M \cdot \Delta V_F$	0.003 W
$\Delta P_{H\text{-}corr}$ as per (18)	6.782 W
$\Delta P_{H\text{-}corr}$ as per (19)	6.743 W
Total error	0.578 %

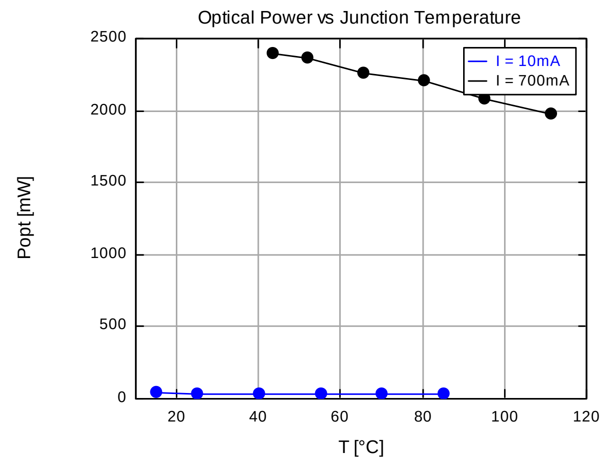

Figure 10 — Heating power calculations and measured values of the emitted optical power for a 4-chip 10W white LED driven by 700 mA heating current and measured by 10 mA sensor current

The I_H/I_M ratio should be determined such that the total error in calculating the heating power remains below 1%. Further factors affecting the choice are the sensitivity (signal-to-noise ratio) of the measurement of ΔV_F and consideration regarding the t_{MD} measurement delay time (5.1.3).

5.1.6 Real thermal resistance / thermal impedance of LEDs

Thermal resistance / impedance of LEDs calculated by equations (10) and (11) using heating power as defined by expression (19) is called *real thermal resistance* / impedance. Thus, real thermal resistance of an LED is obtained from measured data as

$$R_{\Theta JX-real} = \frac{K(I_M)\cdot\left(V_{Fi} - V_{Ff}\right)}{I_H \cdot V_H - I_M \cdot V_{Fi} - \Phi_e(I_H, T_{J1})} \tag{20}$$

and the thermal impedance function is obtained as

$$Z_{\Theta JX-real}(t) = \frac{K(I_M)\cdot\left[V_{Fi} - V_F(T_J(t), I_M)\right]}{I_H \cdot V_H - I_M \cdot V_{Fi} - \Phi_e(I_H, T_{J1})} \tag{21}$$

In order to distinguish the real thermal resistance / impedance calculated by formulae (20) and (21) respectively from the values without considering the emitted optical power as per equations (10) and (11), the notation $R_{\Theta JX\text{-}real}$ and $Z_{\Theta JX\text{-}real}$ shall be used.

5.1 Measurement of LEDs's thermal resistance and junction temperature (cont'd)

5.1.6 Real thermal resistance / thermal impedance of LEDs (cont'd)

Since the radiant flux (emitted optical power) and energy conversion efficiency of any LED depends on the junction temperature (see Figure 10 and Figure 11) special attention should be paid to assure consistency between thermal measurement results and light output measurement results. This means that the radiant flux (emitted optical power) term in equation (19) should be measured at the very same junction temperature which develops when the I_H heating power is applied at thermal tests. *The recommended procedure is to use a single LED testing station which allows combined thermal and radiometric measurement of LEDs*. The light output (P_{opt} or Φ_e) of the LED under test must be measured as described in JESD51-52. Recommendations for the LED testing station are also given in JESD51-52. If such a combined LED testing station is not available, then it must be assured that the same thermal environment is used both for thermal and optical (radiometric) measurements of the LEDs.

There could be sections in the junction-to-case thermal resistance of LEDs which may show temperature dependence such as shown in Figure 12. This figure shows a set of thermal impedances of the same LED by means of structure functions which were measured at different reference temperature values. As shown by the structure functions of Figure 12, the temperature dependent part is the thermal interface material between the MCPCB and the cold-plate. Because of this possible variation, it is advised to measure the thermal resistance of LEDs at least at two different reference temperature values and it is also important to report the value of the reference temperature at which the thermal resistance / impedance was measured[5].

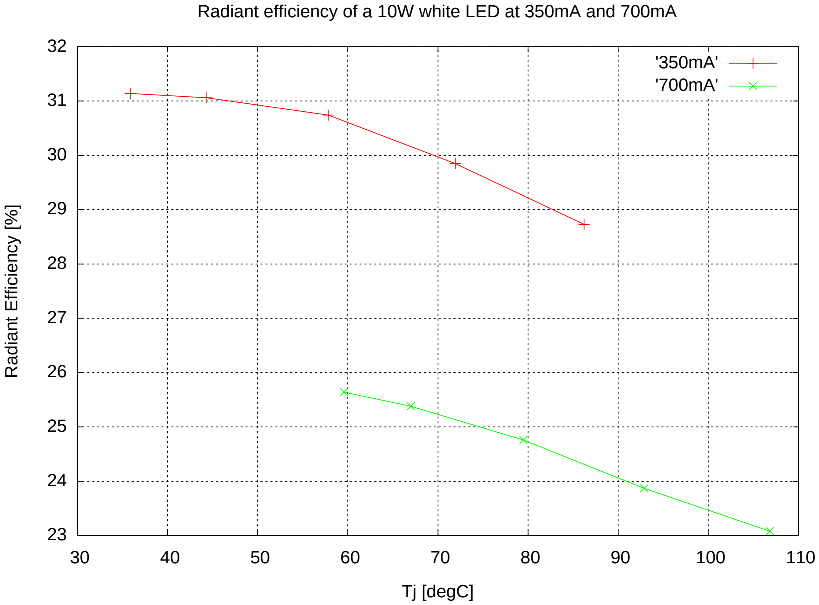

Figure 11 — $\eta_e(I_F, T_J)$ energy conversion efficiency data of a 4-chip 10 W white LED

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[5] Also, this variation of the thermal resistance highlights the importance of applying such an I_M measurement current at which no significant self-heating takes place, since if self-heating takes place during K-factor calibration, the junction temperature would not follow the change of the ambient temperature in the calibration chamber. For details on K-factor calibration refer to 5.3.

5.1 Measurement of LEDs's thermal resistance and junction temperature (cont'd)

5.1.6 Real thermal resistance / thermal impedance of LEDs (cont'd)

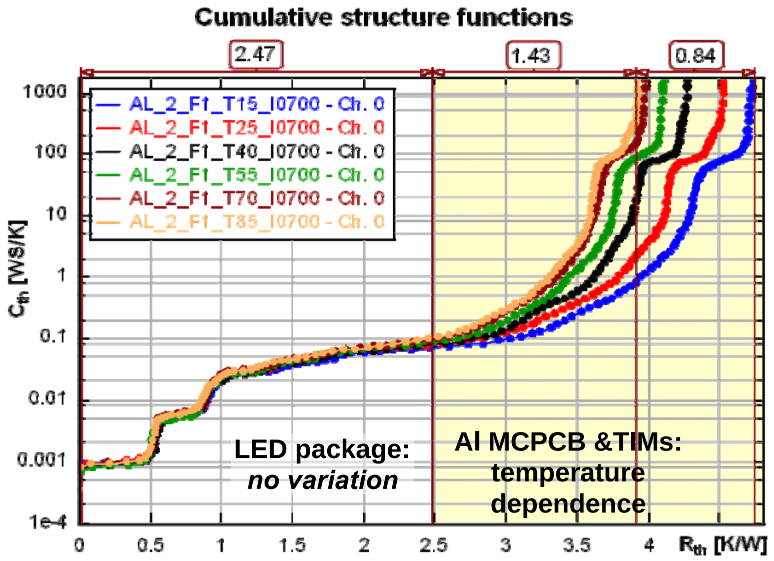

Figure 12 — Structure function representation of the real thermal impedance of 4-chip 10 W white LED attached to a star-shaped MCPCB (measured on a cold-plate)

5.1.7 Calculation of LEDs's real steady-state junction temperature

If the real thermal resistance and the actual heating power of an LED are known at a given reference temperature, then based on equation (3) the real junction temperature can be calculated:

$$T_{J\text{-}real} = P_{H\text{-}corr} \cdot R_{\theta JX\text{-}real} + T_X \tag{22}$$

where $R_{\theta JX\text{-}real}$ shall be measured as defined by equation (20).

Due to the possible temperature dependence of the *total-junction-to-environment X* thermal resistance, the light output characteristics of LEDs should always be reported as function of the real junction temperature calculated for example as per equation (22).

As described in [3], LEDs's junction temperatures can be approximately set to a specified value for all kinds of tests. Because this alternate method of identifying the junction temperature results in an approximate value only, it is recommended to measure back the targeted junction temperature according to equation (22).

The reason for the recommendation of reporting junction temperature according to equation (22) is that this calculation relies on precisely measured parameters – in which data correction accounting for parasitic electrical transients is inherently involved, while so far there exists no standard regarding the implementation of the procedure described in [3], which would require any similar data correction. The error introduced by too long measurement delay during the implementation of this alternate method can be in the order of 5 °C or even higher.

5.2 Procedure for the measurement of R_{th} / Z_{th} of LEDs

5.2.1 The recommended test procedure

The thermal resistance (or thermal impedance) LEDs shall be measured as follows:

1) Mount the LED device onto the test fixture of the specified test environment (e.g., onto a water-cooled cold-plate or onto a thermo-electric cooler based cold-plate as thermal reference environment) whose temperature can be controlled and establish electrical connections to the LED under test as defined in 5.1.1. Make sure that the light output of the LED is not obstructed.
2) Measure the thermal resistance / thermal impedance according to 5.1.2 by performing the steps of the basic static test method of JESD51-1 or by performing the steps of its transient extension as per JESD51-14 as follows:
   a) Apply I_H heating current to the LED under test for a period of t_H as defined in 5.1.4; at the end of the heating period, when the junction temperature got stabilized, perform light output measurements (as described in JESD51-52) if tests are performed in a combined thermal and radiometric LED testing station; record the I_H heating current, the corresponding V_H value of the forward voltage and the measured Φ_e radiant flux (P_{opt}).
   b) Switch from I_H heating current to I_M measurement current and after an appropriately chosen t_{MD} measurement delay time (preferably below 50 µs) record the V_{Fi} initial value of the forward voltage.
   c) If the transient extension of the static test method is performed, continuously record the values of the $\Delta V_F(t)$ function on a logarithmic time-scale with at least 50 points/decade time resolution for a period of t_M measurement time (see JESD51-14, 4.1.2).
   d) After the t_M measurement time has elapsed, measure and record the V_{Ff} final value of the forward voltage or finish recording the $\Delta V_F(t)$ function if transient measurement was performed.
   e) Calculate the heating power according to equation (19) – see 5.1.5.
3) Calibrate the “diode” for use as a temperature sensor – see 5.3.
4) Calculate the thermal resistance from the applied electrical power, emitted optical power, the measured forward voltage change using the temperature sensitivity of the forward voltage according to equation (20) to obtain the real thermal resistance or scale the recorded $\Delta V_F(t)$ function according to equation (21) to obtain the real thermal impedance curve of the LED.
5) Calculate the junction temperature from the known reference temperature, the identified real thermal resistance and heating power according to equation (22)[6].
6) If transient $R_{\Theta JC}$ measurement is performed according to JESD51-14, perform steps 1) through 5) for a different quality of the thermal interface between the cold-plate and the case surface of the power LED and identify the transient $R_{\Theta JC}$ following the procedures of JESD51-14.

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[6] This is a useful procedure to calculate the junction temperature, although the K-factor calibration procedure yields not only the *S* or *K* values but also the absolute forward voltage-temperature relation. However, while typical testers have small offset drift during the 120s measurement time, as calibration and measurement can occur at different days, the calculation from the reference temperature at measurement time even excludes measurement channel offset drift error occurring through more days.

5.2 Procedure for the measurement of R_{th} / Z_{th} of LEDs (cont'd)

5.2.1 The recommended test procedure (cont'd)

7) Report thermal resistance measured at a reference temperature for a typical operating forward current which results in a junction temperature of 25 °C. Junction temperature can be approximately set to 25 °C according to the method described in [3] and can be precisely identified according to equation (22).

8) Optionally, if the LED testing station allows, repeat steps 1) through 7) for various values of the reference temperature including 25 °C, 55 °C and 85 °C (values also recommended by ANSI/IESNA IES-LM-80). Based on the measurement results calculate the corresponding junction temperatures according to equation (22) and report the LED efficiencies and all the measured light output characteristics as functions of these junction temperatures.

5.2.2 The test apparatus

Based on the recommendations of MIL-STD-750D Method 3101.3, the apparatus required for thermal testing of LEDs shall include the following, configured as shown in Figure 6:

- A constant current source capable of adjustment to the desired value of I_H and able to supply the V_H value required by the DUT. The current source should be able to maintain the desired current within ±1 % during the entire length of heating time.
- A constant current source to supply I_M with sufficient voltage compliance to turn the TSP of the pn-junction fully on.
- An electronic switch capable of switching between the heating period conditions and measurement conditions in a time frame short enough to avoid DUT cooling during the transition; this typically requires switching in the microsecond or tens of microseconds range.
- A voltage measurement circuit capable of accurately making the V_{Ff} measurement within the time frame with 0.1 mV resolution or better.

5.3 Forward voltage stability and K-factor calibration of LEDs

Most LEDs are fabricated from complex multi-element semiconductor materials that do not yet have the process consistencies associated with most silicon devices. Further, some types of LED devices need some operating burn-in time in order to "anneal" the junction. The result is that without the burn-in time, the diode forward voltage (V_F) for a given applied forward current (I_F) may significantly vary when the same I_F is repeatedly applied. Therefore *it is recommended, that all LED samples to be tested are burnt-in* to assure repeatability of tests[7]. Also, the K-factor (reciprocal of the S_{VF} temperature sensitivity of the forward voltage) shows large sigma variations between before and after burn-in and even after burn-in, there are still huge variations among LED samples from the same manufacturing lot.

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[7] Vendor dependent. Some LED vendors' devices are stable when shipped, they do not need burn-in. Long-term stability of LEDs is still subject of research. Among many operational parameters such as luminous flux, color temperature forward voltage may also vary over long period of time. This time is in the order of magnitude of thousand hours and above. Forward voltage variations in such time-frame do not endanger accuracy of testing of selected test LED samples if they are already burnt-in and K-factor calibrated.

5.3 Forward voltage stability and K-factor calibration of LEDs (cont'd)

The K-factor is the correlation between the LED junction V_F, forward voltage, (measured at a constant forward current) and the T_J, junction temperature. The K-factor calibration procedure consists of placing the measurement sample into a temperature-controlled environment and then allowing the T_J, junction temperature, of the sample to reach steady state with its surrounding ambient temperature (T_A in Figure 13) while being powered by a small constant I_M, measurement current. The V_F is recorded and the procedure is repeated at one or more different T_A values. The data is then plotted (T_J vs V_F) and slope of the resultant straight line becomes the K-factor in units of K/mV. *It is recommended that at least 3 temperature values are applied in K-factor calibrations*[8].

If a sample lot of ten LEDs from the same production run is subjected to K-factor calibration before and after a 24-hour operating burn-in process, the typical ratio of K-factor standard deviations to the lot-averaged K-factor will change dramatically as shown in Table 2.

Table 2 — K-factor standard deviations

	Typical σ_K/K_{Avg} [%]
LED lot before operating burn-in	>10
LED lot after operating burn-in	3 → 7
Silicon rectifier of comparable current capability	<1

The impacts of these results are several. First, thermal measurements on LED devices before properly burnt-in may lead to significant measurement data errors. Second, the high value of the σ_K/K_{Avg} ratio dictates that the K-factor for each LED must be used in the thermal resistance data generation. Therefore, *each LED to be tested must be individually calibrated to obtain its specific K-factor*[9]. It has to be noted that the K-factor depends on the applied I_M, measurement current, therefore it is important that the same I_M, measurement current, is being used during junction temperature measurement (section 0) which was used in the K-factor calibration procedure.

The temperature sensitivity of the forward voltage of pn-junctions can be derived from the ideal diode characteristic:

$$I_F = I_0 \cdot \left[\exp(V_F / nV_T) - 1\right] \tag{23}$$

or rearranging for forward voltage (considering the electrical series resistance as well):

$$V_F = nV_T \ln\left(I_F / I_0\right) + I_F \cdot R_S \tag{24}$$

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[8] To assure consistency among different tests of LED products, case temperature values specified in section 4.4.2 of ANSI/IESNA IES-LM-80 (55°C and 85°C) and as a third temperature value, laboratory temperature (25°C) – are suggested to be used during K-factor calibration of LEDs.

[9] This is a major deviation from recommendations of former pn-junction testing standards such as MIL-STD-750D METHOD 3101.3.

5.3 Forward voltage stability and K-factor calibration of LEDs (cont'd)

The final result of the calculation of the $S_{VF} = dV_F/dT_J$ differential is as follows:

$$\frac{dV_F}{dT_J} = \frac{V_F}{T_J} - \frac{V_{G0} + m \cdot n \cdot V_T}{T_J} = \frac{nV_T \ln\left(I_F / I_0\right) + I_F \cdot R_S}{T_J} - \frac{V_{G0} + m \cdot n \cdot V_T}{T_J} \tag{25}$$

where

$V_T = (k{\cdot}T)/q$ is the thermal voltage (~26mV at around room temperature, k is Boltzmann's constant, T is the absolute temperature of the semiconductor, q is the elementary charge);
n is the so called *emission factor* or *ideality factor* of the pn-junction (typical values are between 1 and 2);
m is the power factor in the temperature dependence of the I_0 saturation current (typical value is 3);
V_{G0} is the nominal value of the bandgap voltage of the semiconductor material.

NOTE In equation (25) the junction temperature should be substituted in Kelvins (see also JESD51-1, 2.1.2).

In case of LED arrays, e.g., in the series configuration (Figure 3a), junction temperature change induced variation of the forward voltages of the individual LEDs add-up, therefore temperature sensitivity of the overall (ensemble) forward voltage of the LED line is the sum of the temperature sensitivities of the individual forward voltages:

$$S_{VF-ensemble} = \sum_{i=1}^{n} S_{VFi} \tag{26}$$

where

S_{VFi} denotes the temperature sensitivity of the forward voltage of the i-th LED in the linear array;
n is the number of the LEDs connected in series.

Figure 13 shows a possible K-factor calibration setup in which forward voltage measurement is performed by the thermal test equipment with which the final measurements will also be done (as shown in Figure 15). Certainly, any high precision laboratory current source and voltage meter can also be used during K-factor measurement (see also recommendations of JESD51 and MIL-STD-750D Method 3101.3).

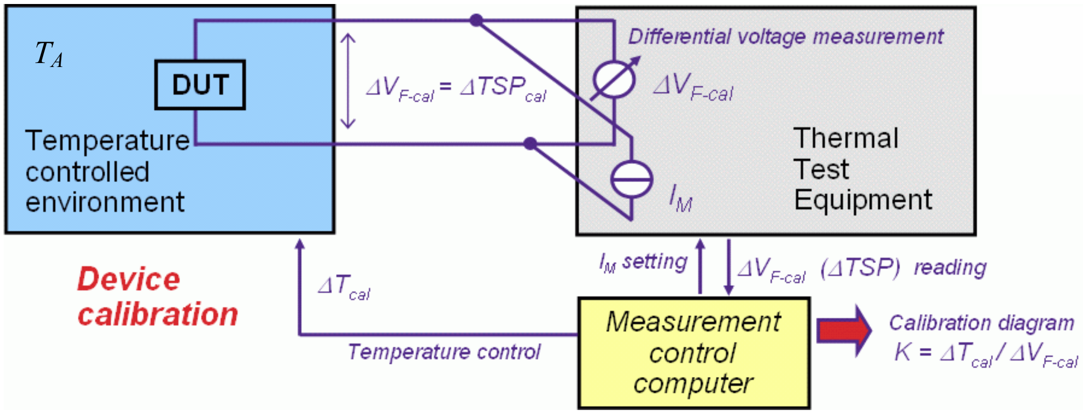

Figure 13 — Suggested setup for K-factor calibration of LEDs

5.3 Forward voltage stability and K-factor calibration of LEDs (cont'd)

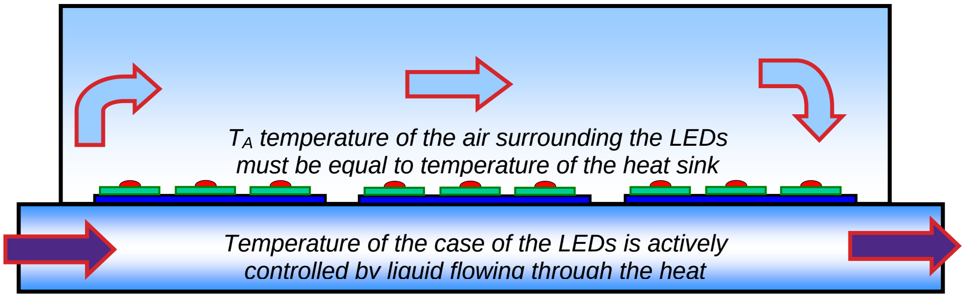

Figure 14 — Example for a temperature controlled chamber for K-factor calibration of LEDs. The arrangement shown here complies with the recommendations of ANSI/IESNA IES-LM-80 tests. Any other test arrangement which assures that a medium with uniform temperature surrounds the LEDs is appropriate for K-factor calibration.

The *ensemble K-factor of the an LED array* is

$$K_{ensemble} = 1/S_{VF\text{-}ensemble} \tag{27}$$

The K-factor shall be calculated as follows:

$$K = \frac{\Delta T_{cal}}{\Delta V_{F-cal}} \tag{28}$$

where

ΔT_{cal} is the total variation of the T_A ambient temperature of temperature controlled calibration environment applied during the calibration process: $\Delta T_{cal} = T_{A\text{-}Hi} - T_{A\text{-}Lo}$;
$\Delta V_{F\text{-}cal}$ is the difference of the forward voltage readings at $T_{A\text{-}Hi}$ and $T_{A\text{-}Lo}$ temperatures (see also equation (9) in JESD51-1).

During K-factor calibration the following recommendations should be kept:

- In order to avoid contamination of the lens of the LED device, *liquid (oil) bath as temperature controlled test environment must be avoided*. Instead, for example, MCPCB mounted LED assemblies shall be mounted to a cold-plate with accurate temperature control and it should be assured, that the air surrounding the LED device is forced to the same temperature as the temperature of the cold-plate. Ovens or temperature controlled chambers which are similar to the ones used in lumen maintenance tests described in ANSI/IESNA IES-LM-80 can be used with the following restrictions: the accuracy of the case (heat sink) temperature control should be at least 0.5 ^{o}C as it concludes from the recommendations of JESD51-1. Figure 14 shows an example for a temperature controlled chamber in which K-factor calibration of multiple LEDs can be performed.

- Temperature stability shall be determined as follows: if the ambient temperature variation has been below 0.5 ^{o}C for more than 5 minutes and junction forward voltage has been stable for 2 minutes, then the LED being calibrated is considered to be stabilized in temperature. In case of single junction LED devices junction forward voltage can be considered to be stable, if the variation of the forward voltage shrinks below 1 mV in the 2 min time window, which corresponds roughly to the junction temperature variation of 0.5 ^{o}C. In case of LED devices with multiple LED pn-junctions connected in series, this forward voltage variation limit shall be multiplied with the number of junctions connected in series. The actual ambient temperature (not the set point) has to be recorded since these values shall be used to calculate the ΔT_{cal} used in equation (28).

5.3 Forward voltage stability and K-factor calibration of LEDs (cont'd)

- Total temperature change of the T_A, ambient temperature, of the temperature controlled calibration chamber should be 50°C (as prescribed by JESD51-1) or the predicted ambient temperature change of the LED under test in real-life application – whichever value is larger.

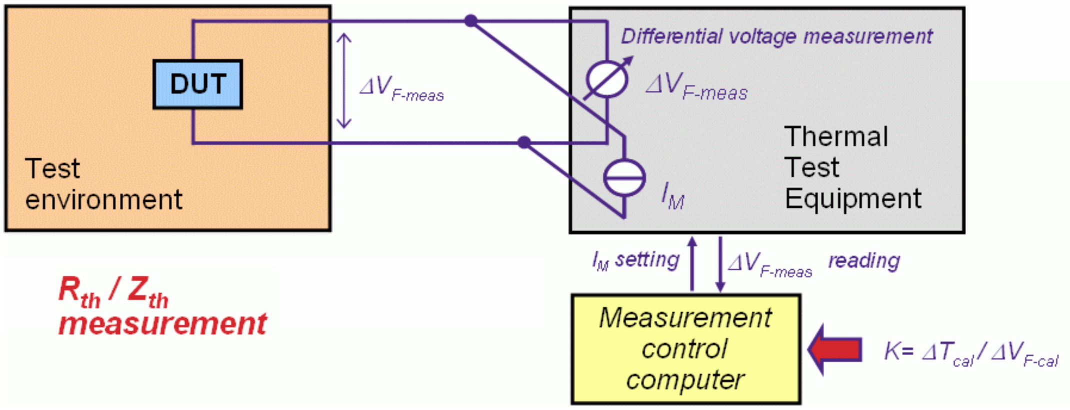

Figure 15 — It is suggested to use the same I_M current source and the same voltage measurement device during actual thermal testing as the ones used for K-factor calibration

As advised earlier, to assure the highest possible overall accuracy of the measurements, the following are suggested (see Figure 13 and Figure 15):

- use the same measurement current source during K-factor calibration and actual measurement,
- use the same voltage meter device during K-factor calibration and actual measurement,
- measure the *change* of the TSP voltage (forward voltage), preferably in differential mode in order to eliminate offset error of the voltage measurement device.

By having the same current source for providing the I_M measurement, it is assured that the S_{VF} temperature sensitivity of the LED is the same during thermal test as it was during K-factor calibration. Using the same voltmeter assures that the offset error and the scale error of the voltage meter cancels out from the value of the identified junction temperature change, since

$$\Delta T_{measured} = K \cdot \Delta V_{F-meas} = \Delta T_{cal} \cdot \frac{\Delta V_{F-meas}}{\Delta V_{F-cal}} \tag{29}$$

where

$\Delta V_{F\text{-}meas}$ is the measured forward voltage change as a response to the ΔP_H change in the dissipated power. Using the notations of Figure 7, $\Delta V_{F\text{-}meas} = V_{Ff} - V_{Fi}$.

The ΔT_{cal} , temperature range of the calibration, shall be calculated from the recorded values of the ambient temperature values that are actually reached by the temperature controlled calibration environment.

6 Bibliography

[1] Székely, V. and T.V. Bien, "Fine Structure of Heat Flow Path in Semiconductor Devices: A Measurement and Identification Method", *Solid-State Electronics*, Vol.31, No. 9, 1988, pp. 1363-1368.

[2] Székely, V., "Identification of RC Networks by Deconvolution: Chances and Limits", *IEEE Transactions on Circuits and Systems I – Fundamental Theory and Applications*, Vol. 45, No. 3, 1998, pp. 244-258.

[3] Zong, Y. and Y. Ohno, "New practical method for measurement of high-power LEDs", *Proceedings of the CIE Expert Symposium 2008 on Advances in Photometry and Colorimetry*, CIEx033-2008, 2008, pp.102-106.

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1. I recommend changes to the following:

☐ Requirement, clause number ____________

☐ Test method number ____________ Clause number ____________

The referenced clause number has proven to be:

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☐ Other ____________

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2. Recommendations for correction:

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